NMR T_2 CUT OFF: WHICH ONE IS TO BE USED FOR APPLICATION?

by

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ABSTRACT

Recent developments in petroleum industry have been witnessing the surge of the use of nuclear magnetic resonance (NMR) log. Despite some remaining problems the NMR technology appears to gain more acceptance as petrophysical tool for evaluating reservoir quality. Comprehensive formation evaluation requires determination of irreducible fluids, movable fluids, and permeability. However, rock heterogeneity introduces complexity in any formation evaluation activities. This can also cause problem for NMR log interpretation. In the presence of clays the most commonly used T_2 *cut off values, a constant value throughout a formation, seem to eventually yield inaccurate irreducible water saturation estimates, as well as other output such as permeability. This study focuses at finding a solution for finding the best way of choosing the most representative* T_2 *cut off value to be used in NMR log interpretation. This is indeed a common pressing problem for heterogeneous formation rocks such as in the case of Tirrawarra sandstones used in this study. The main part of the study is devoted to comparison between the use of single averaged* T_{2c} *value and establishment of empirical correlations enabling the provision of* T_{2c} *for any level of heterogeneity (i.e. various levels of shaliness). The study however surprisingly shows that, in spite of the theoretical soundness of the empirical correlations established, simple averaging of* T_{2c} *values yielded by a reliable method proves itself adequate. This conclusion therefore helps considerably in reducing complexity in NMR log interpretation.*

Key words: T_{2c}*, irreducible water saturation, ductile components, empirical correlation, averaged* T_{2c}*.*

I. INTRODUCTION

Nuclear magnetic resonance (NMR) log is at present gaining momentum in its use in petroleum industry. Despite the ever remaining controvercy over its consistencies in measurement accuracy, the method is fast achieving recognition as a petrophysical tool for evaluating various reservoir properties including volumes of movable and irreducible fluids, permeability, and effective porosity. Such properties like irreducible water saturation are acknowledged for its importance in the estimation of hydrocarbon in place and reserves and reservoir productivity.

Earlier studies on the applications of NMR technology in assessing permeability, effective porosity, and irreducible fluid in heterogeneous formations have been carried out by some studies in the past (e.g. Kenyon, 1989; Straley *et al*., 1991; Kenyon, 1992; Prammer *et al*., 1996; Coates *et al*., Coates *et al*., 1995; 1994; Coates *et al*., 1997; Oraby *et al*., 1997; Hassoun *et al*., 1997; Hodgkins & Howard, 1999). Results of these investigations have indicated that for some particular sandstone samples with significant amount of clay content, a detailed knowledge and understanding of reservoir properties including lithology and mineral composition are essential to apply and to interpret NMR measurement data.

In order to divide effective porosity into movable and irreducible fluid saturations, NMR measurements require a T_2 cutoff, or often expressed as $T_{2c..}$ In traditional T_2 interpretation, the T_{2c} is usually taken as a constant value throughout a formation. However, this proved to be impracticable, and in many cases resulting in inaccurate permeability and irreducible water saturation values (S_{wirr}). Since this inaccuracy is suspected to be due to the sandstone's nature of heterogeneity in lithology and mineral composition, it was therefore thought that a different approach should be adopted. Musu (2000) and Musu & Widarsono (2007) suggested that for rocks such as shaly sandstones as many as possible T_{2c} should be taken to accommodate the high heterogeneity level. Accordingly, different T_{2c} was measured for each of the sample used in the study using which – naturally – better permeability and irreducible water saturation (S_{wirr}) were resulted.

In Musu (2000) and Musu & Widarsono (2007) it has been shown that the BVI Error method, a method that is basically an iterative approach, produced the most representative T_{2c} for individual sample. However, the method does not offer a solution that suggests the choice of T_{2c} to be applied in practical NMR log interpretation. It is therefore the purpose of this study to find the best way to assign the best T_{2c}.

II. DETERMINATION OF T_2 CUT OFF (T_{2c})

The comprehensive study presented in Musu (2000) was carried out on a set of Tirrawarra shaly sandstone samples taken from Cooper Basin, South Australia. In reaching its objectives the study used results from petrographic, NMR, routine core analysis, special core analysis, and mercury intrusion capillary pressure (MICP) data for the sandstone samples.

NMR measurements refer to the response of hydrogen nuclei (protons) to a magnetic field. Hydrogen nuclei are abundant in both water and hydrocarbons stored in formation. NMR tools basically measure the decaying signals of the nuclear spin of protons in the water and hydrocarbons at various times. The signal decaying time required for the protons to complete de-phasing is termed T_2. The NMR measurements of amplitude versus time are used to calculate the distribution of porosity components (T_2 distribution) as a function of their T_2 times.

T_2 cut off, or T_{2c}, is the maximum T_2 for part of porosity that is occupied by immovable fluids. It is used to distinguish movable fluid (FFI) from the irreducible or non-movable fluid (BVI). In the T_2 distribution, BVI is all the amplitudes in the spectrum having T_2 values less than the T_{2c}. In other words, T_{2c} is the sum of all porosities whose T_2 is less than the T_{2c} and consequently FFI is the sum of amplitudes with T_2 values greater than T_{2c}, or the sum of all porosities whose T_2 is greater than T_{2c}. Therefore, it is obvious that correct determination of the T_{2c} is very important for estimation irreducible water saturation. The following is brief discussion over the approaches used for T_{2c} determination. Detailed description of the methods is presented in Musu (2000) and Musu & Widarsono (2007).

A. *T_{2c} by default*

For T_{2c} application in interpretation and analysis, two common T_{2c} values are often used for sandstone formations. Those T_{2c} values of 33 ms (Morris *et al*., 1993; Coates *et al*., 1999) and 22.6 ms (Numar-Halliburton standard for sandstone) are established based on combination of field experience and extensive laboratory data.

B. *T_{2c} direct from spectrometer*

T_{2c} values are usually calibrated in the laboratory using plugs obtained from conventional cores. Measurements are performed by matching the integrated NMR amplitudes up to T_{2c} in the T_2 spectrum measured for a water saturated-core sample to the volume of water remaining in the core after de-saturating to a desired capillary pressure (Straley *et al.*, 1994).

Under certain formation conditions an average value of core-measured, single or fixed T_{2c} method is inappropriate. For the Tirrawarra Sandstone sample set used in this study, presence of significant amount of ductile clay and quartz cementation has caused the development of micro-porosity with macro-pores tend to be isolated leading to low permeability.

The average standard T_{2c} computed from the NMR spectrometer for the samples provided is 42 ms, which corresponds to values of individual samples that range from 18.56 ms to 57.15 ms. This variance indicates that a single T_{2c} method would not properly represent BVI, which in turn would give incorrect permeability and S_{wirr}.

C. *T_{2c} using SBVI method*

The spectral bulk volume irreducible (SBVI) method is based on the T_2 distribution and has utilized core-measured values of BVI to determine the percentage of amplitude (porosity) associated with each individual T_2 which will remain as capillary-bound water (Coates *et al*., 1997; Santos-Numar, Cooper core sample study, 1999; Oraby *et al*., 1997). SBVI varies T_{2c} by measuring the contribution of the irreducible fluid to the overall fluids in each grouping or bin of the T_2 distribution. These measured values are used to calculate the irreducible water, S_{wirr} in each bin. The S_{wirr} values of all the bins are then fitted against their T_2 values through the use of a function of

$$S_{wi} = \frac{1}{mT_{2GM} + b} \tag{1}$$

where m is fitting parameter, b is y-intercept, and T_{2GM} is the geometric mean of the T_2 values (Coates *et al*., 1997) of the regression line shown in Figure 2. The variable m was determined as the slope of the line relating $1/S_{wi}$ (core derived) to the geometric mean T_2 (T_{2GM}), which gives m of 0.013 for b taken as equal to 1 (sandstone) (Coates *et al*., 1997). SBVI is then derived by multiplying S_{wirr} and NMR porosity (MPHI). Geometric mean T_2 (T_{2GM}) values were obtained from fully brine saturated samples. (Figure 1 shows a very poor fit suggesting that this method may not be valid in this particular sample set known for their significant amount of ductile and clay components.)

D. T_{2c} *using BVI Error method*

To ensure the acquisition of representative BVI values, a 'BVI error' method was applied. In the method, T_{2c} was estimated through comparing core-derived irreducible water volume (V_{wirr}) to NMR cumulative porosity. The core-derived V_{wirr} itself is actually a multiplication product of core irreducible water saturation (S_{wirr}) and core porosity. It is assumed that this measured irreducible water saturation is a true measure of BVI against which the BVI derived from the NMR can be compared to. T_{2c} values considered representative are obtained when the BVI values from the NMR data are in the least disagreement or least in error with the corresponding V_{wirr} values. To observe the T_{2c}, the absolute difference between the NMR cumulative porosity data and core data is plotted against T_2 on the NMR tabular sheets (for the brine-saturated measurements). In such a plot T_{2c} for each sample is characterized by a minimum sharp plunge of the cumulative curves (Figure 2). See Musu (2000) for complete discussion regarding procedure.

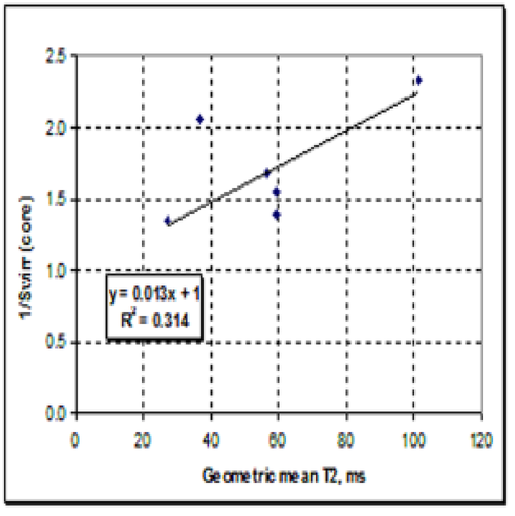

Figure 1
Cross-plot of geometric mean T_2 (T_{2GM}) versus 1/core Swirr for determination of SBVI model (from Musu, 2000)

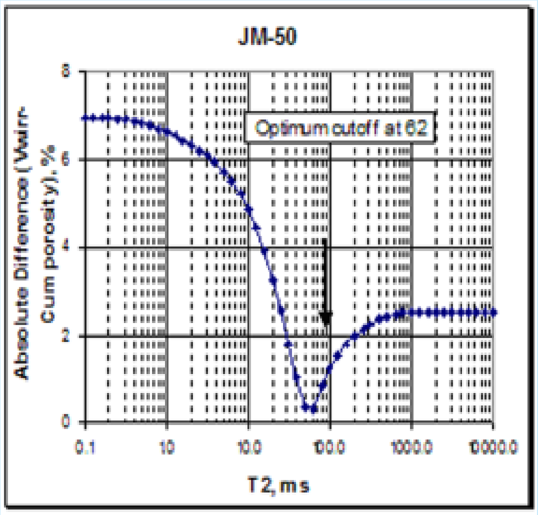

Figure 2
T_{2c} determination using BVI error method. T_{2c} for each sample is determined by the sharp plunge on the cumulative curve (example is sample JM-50 with T_{2c} at 62ms) (from Musu, ….)

III. MEASURED NMR RELAXATION TIME (T_2) DISTRIBUTIONS

NMR relaxation time distributions for fully brine-saturated samples are broad, ranging between less than one and more than 1,000 milliseconds (Figure 3). The distributions commonly encountered are of skewed unimodal type, which usually does not clearly differentiate between inter-granular porosity and micro-porosity. However, unimodal distribution shown by the relaxation time distribution might be interpreted as a combination of two or more sub-populations (Swan & Sandilands, 1995) interpreted as micro-porosity and macro-porosity.

In NMR T_2 measurement, partial saturations were obtained by centrifuging the water-saturated samples. The irreducible water or non-centrifugeable water includes clay bound water and capillary bound water. NMR relaxation time distributions for partially saturated samples are also broad, ranging from zero to nearly 1,000 milliseconds (Figure 3). The distributions commonly encountered are trimodal, which might be associated with small and larger pores. A trimodal distribution with a broad range of T_2 distribution is usually taken as an indication that bound fluid is not only associated with small pores but also with larger pores (FFI). The trimodal curves show that the water is present not only in the small pores but also in the larger pores.

IV. DETERMINATION OF IMMOVABLE WATER (BVI)

As mentioned above, movable and immovable water were determined using the T_{2c} on T_2 relaxation curves. In order to correlate BVI with the core derived irreducible water saturation (S_{wirr}), the BVIs were then calculated as percentages. The BVI as a percentage is then termed as NMR $S_{wirr.}$. As reported in Musu (2000), S_{wirr} values derived using a single and predetermined T_{2c} values show very poor agreements with the core-derived S_{wirr} values (Table 1). On the contrary, S_{wirr} values calculated using representative T_{2c} values produced through the use of BVI error method and the T_{2c} measured directly from the NMR machine tend to show very good agreements with the core measurements (Table 2).

The varied T_{2c} determined by the SBVI method, however, gives weaker correlation between NMR S_{wirr} and core S_{wirr}. SBVI results demonstrate inappropriate BVI values. The T_{2c} determined by SBVI is based on mean geometric T_{2c}, measured directly from the spectrometer and do not include the effect of reservoir heterogeneity (Oraby et al., 1997). As the representative T_{2c} values for the samples are known S_{wirr} can then be estimated reliably.

The comparison between NMR S_{wirr} and core S_{wirr} values can also be presented graphicaly. Figures 4 through 11 present the plots, respectively, for T_{2c} = 22.6 ms (Numar-Halliburton), T_{2c} = 33 ms (Morris et al., 1993), varied T_{2c} values from spectrometer, average value from spectrometer of T_{2c} = 42 ms, varied T_{2c} values from SBVI method, average value from SBVI method of T_{2c} = 56.6 ms, varied T_{2c} values from BVI Error method, and average value from BVI Error method of T_{2c} = 66.5 ms.

Table 1
Results of irreducible water saturation (S_{wirr}) using single T_{2c} (22.6 ms). Notice the disagreement between estimated S_{wirr} and observed (core) S_{wirr} (from Musu, 2000)

Sample	T_{2c} (ms)	MPHI (%)	BVI (%)	FFI (%)	Swirr (%)	Swirr (core) (%)
JM-11	22.6	14.601	2.986	11.615	20.451	64.2
JM-12	22.6	14.527	2.775	11.752	19.102	71.9
JM-26	22.6	13.87	5.213	8.657	37.585	48.7
JM-42	22.6	12.371	2.795	9.576	22.593	59.5
JM-50	22.6	9.459	4.23	5.229	44.719	74
JM-53	22.6	11.75	1.924	9.826	16.374	43

Table 2
Results of irreducible water saturation (S_{wirr}) using multiple representative T_{2c} values from BVI Error method. Notice the good agreement between estimated S_{wirr} and observed (core) S_{wirr} (from Musu, 2000)

Sample	T_{2c} (ms)	MPHI (%)	BVI (%)	FFI (%)	Swirr (%)	Swirr (core) (%)
JM-11	22.6	14.601	8.595	6.006	58.866	64.2
JM-12	22.6	14.527	9.412	5.115	64.79	71.9
JM-26	22.6	13.87	6.466	7.404	46.619	48.7
JM-42	22.6	12.371	6.588	5.813	53.011	59.5
JM-50	22.6	9.459	7.189	2.27	76.002	74
JM-53	22.6	11.75	4.766	6.984	40.562	43

From the plots it can be clearly seen that results from BVI Error method are the best indicated by the very small disagreement when the results are compared to core data (Figure 10). The two predetermined T_{2c} of 22.6 ms and 33.3 ms appear to have yielded largely inaccurate results. This underlines the urgency of laboratory measured T_{2c} value for most of cases especially the heterogeneous ones such as Tirrawarra sandstones. The representation of averaged values also seem to have not improved the results either even though their results can still be considered as better than results from the two predetermined T_{2c} values.

V. WHICH T_{2C} SHOULD BE ADOPTED?

As shown by the plots presented on Figures 4 through 11, the BVI Error method appears to be yielding the best S_{wirr} estimates if the S_{wirr} values from core are to taken as reference. However, a question remains over the representative value to be used for interpreting NMR log data. There are some options that can be taken to deal with this question; averaging the available T_{2c} values, establishing a kind of mathematical function that represents the whole range of T_{2c} values, choosing one of the T_{2c} values available, and picking a T_{2c} value within the range of T_{2c} values. Among the options, the first option has been performed and the result is presented in Figure 11. The remaining three options are to be tested here.

The effort to establish a mathematical function is started from a consideration about the relevant factor that is linked to T_{2c}. It was initially thought that it should be porosity and permeability due to their significant influence on S_{wirr}. However, although this may theoretically and empirically be correct this can be considered as impractical since porosity and permeability are also the output of NMR log. Moreover, wells that are NMR-logged may not have porosity and permeability data from other sources. Another factor that could be considered as important is the major source of heterogeneity itself in the case of Tirrawarra sandstones, presence of ductile components.

The ductile components in the Tirrawarra sandstones are defined as composed by rock fragments, matrix (pore filling fine particles, and clay minerals. These materials cause ductility behaviour in the rocks and serve as the major factor in the creation of isolated pores hence changing effective porosity, permeability, and irreducible water saturation. Comprehensive disscussion regarding this matter is presented in Musu & Widarsono (2007). Based on this evidence the T_{2c} is to be made as a function of contents of ductile components.

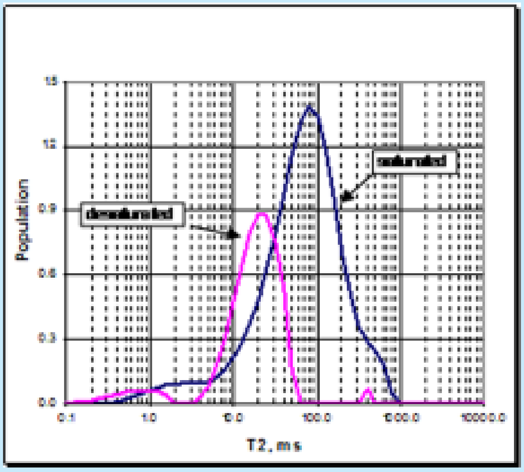

Figure 3
Typical NMR relaxation time, as also exhibited by the Tirawarra sandstones used in the study (from Musu, 2000)

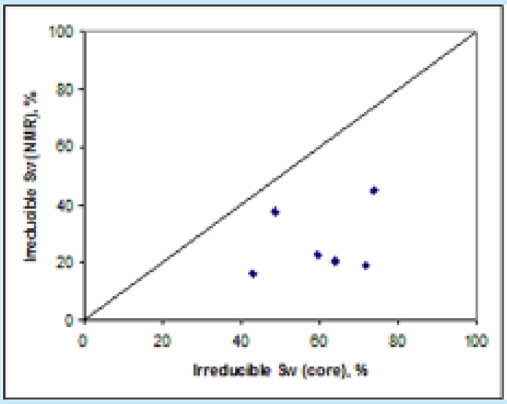

Figure 4
Comparison between core S_{wirr}.
and NMR S_{wirr} estimated using T_{2c} = 22.6 ms

Table 3 presents the ductile components for the six core samples used in the study along with the T_{2c} values from the BVI Error method. Early effort to plot ductile components versus T_{2c} values proves to be too scattered to yield any reliable correlation. Therefore, a sort of compromise has to be reached. In this light, T_{2c} values for JM-11 and JM-12 samples appear to be ‘too high’ and need adjustment. With

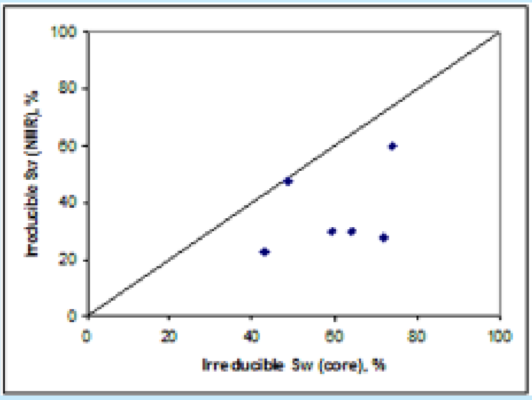

Figure 5
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using T_{2c} = 33.3 ms

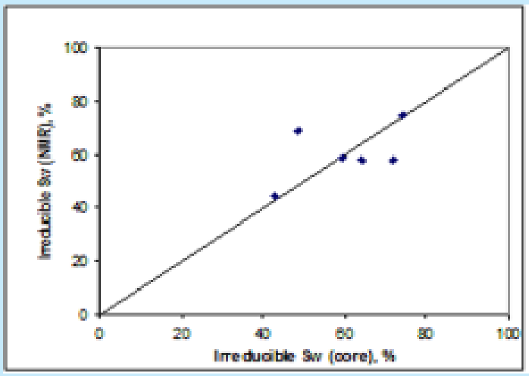

Figure 8
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using varied T_{2c} values determined using SBVI method

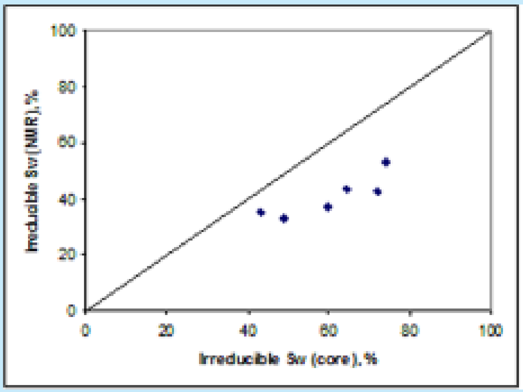

Figure 6
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using varied T_{2c} values determined directly using NMR spectrometer

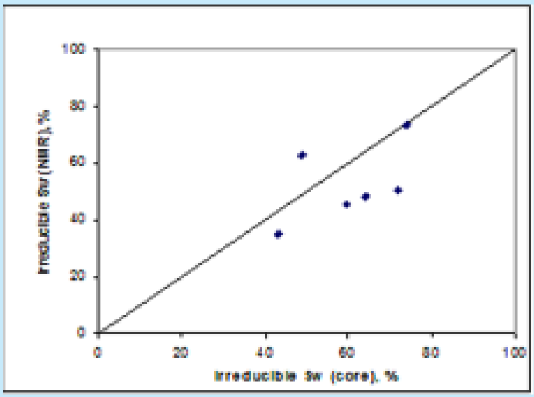

Figure 9
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using average value of T_{2c} = 56.6 ms from values determined using SBVI method

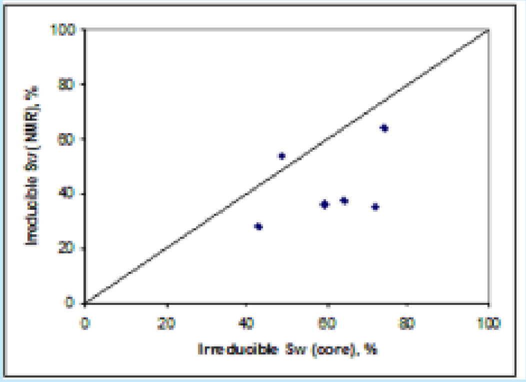

Figure 7
R S_{wirr} estimated using average value of T_{2c} = 42 ms from values determined directly using NMR spectrometer

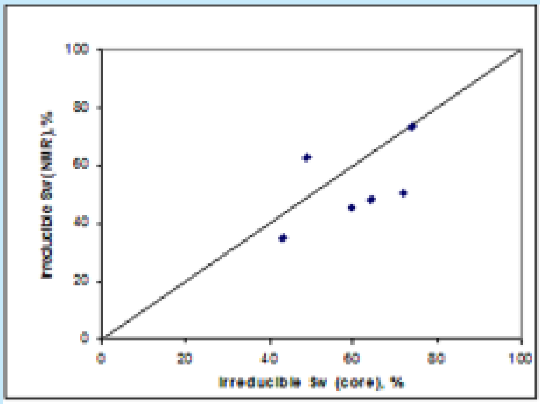

Figure 10
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using varied T_{2c} values determined using BVI Error method

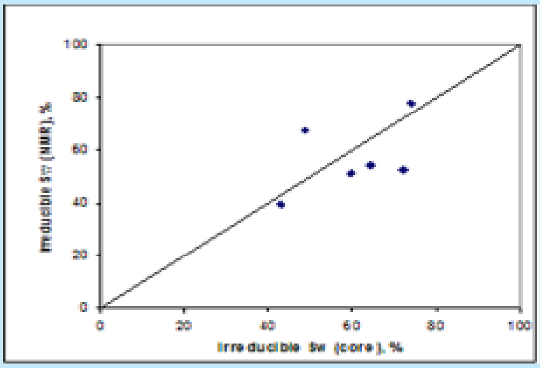

Figure 11
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using average value of T_{2c} = 66.5 ms from values determined using BVI Error method

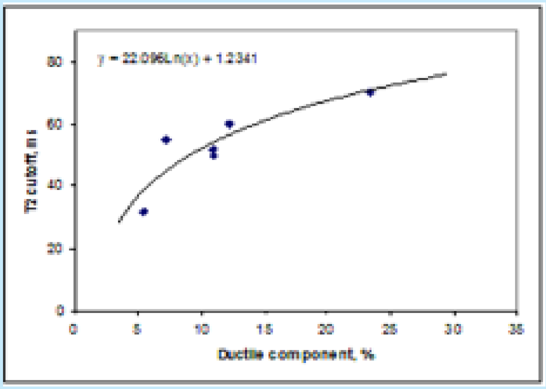

Figure 12
Logarithmic correlation between T_{2c} (compromised) and ductile component

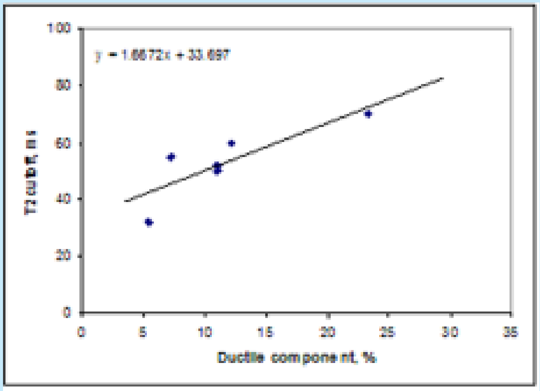

Figure 13
Linear correlation between T_{2c} (compromised) and ductile component

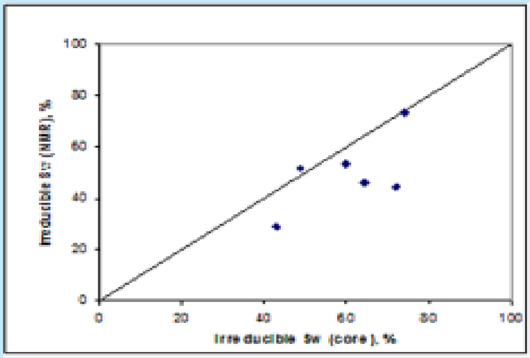

Figure 14
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using varied but compromised T_{2c} values determined using BVI Error method (logarithmic correlation)

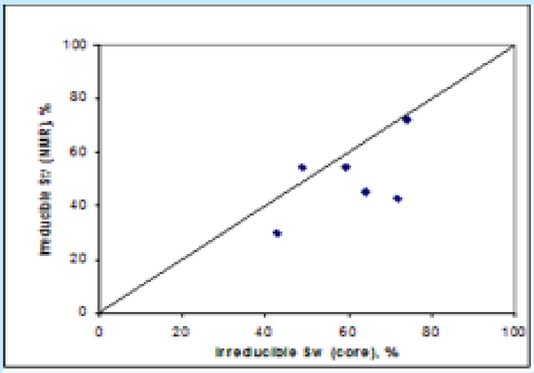

Figure 15
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using varied but compromised T_{2c} values determined using BVI Error method (linear correlation)

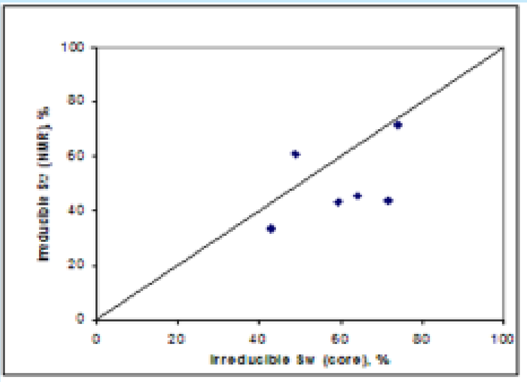

Figure 16
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using average T_{2c} = 53.67 ms from compromised values that are modified from values yielded by BVI Error method

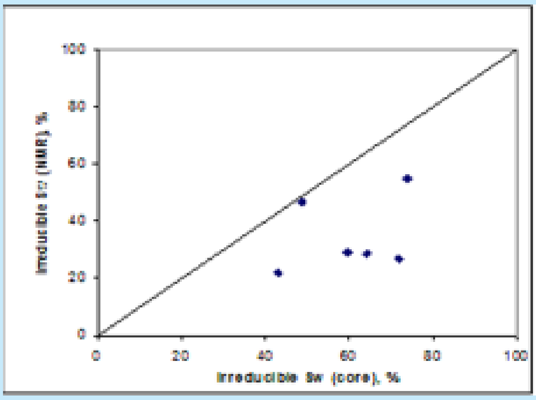

Figure 17
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using T_{2c} = 32 ms from BVI Error method

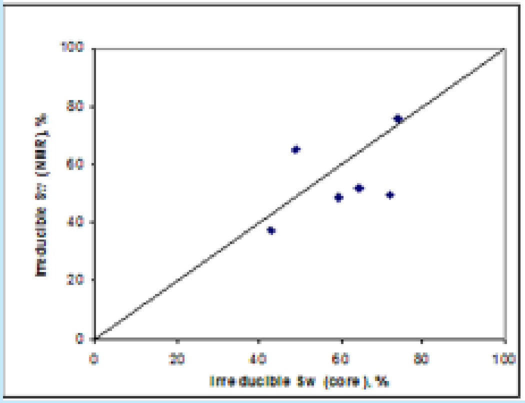

Figure 18
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using T_{2c} = 62 ms from BVI Error method

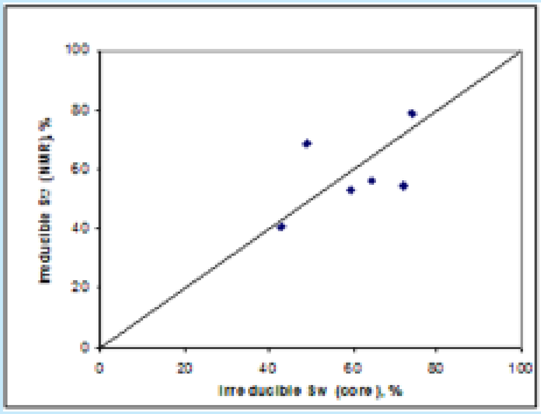

Figure 19
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using T_{2c} = 70 ms from BVI Error method

Table 3
Ductile components, T_{2c} from BVI Error method, and compromised T_{2c} values (from Musu, 2000)

Sample	Ductile components (%)	T_{2c} (ms)	T_{2c} (compromised) (ms)
JM-11	11	75	50
JM-12	11	90	52
JM-26	5.4	32	32
JM-42	23.3	70	70
JM-50	12.2	62	60
JM-53	7.17	70	55

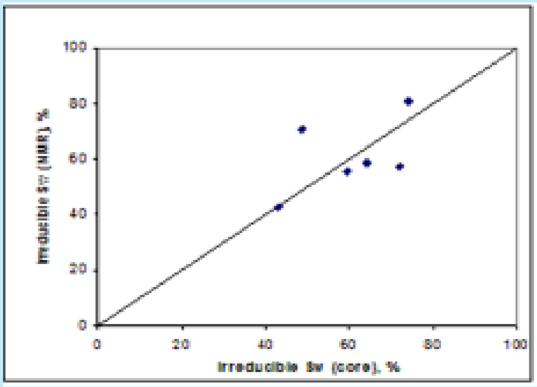

Figure 20
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using T_{2c} = 75 ms from BVI Error method

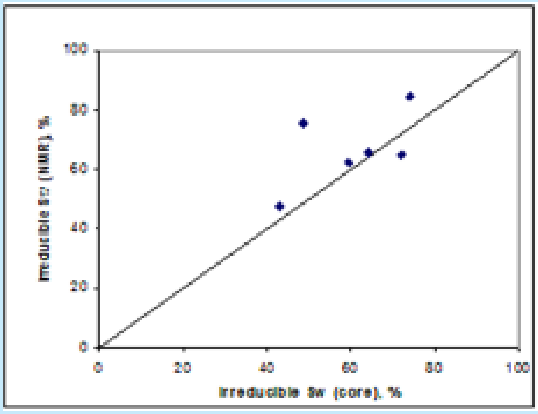

Figure 21
Comparison between core S_{wirr}.and NMR S_{wirr} estimated using T_{2c} = 90 ms from BVI Error method

taking into consideration the possible error in measurement and presence of anomalous data the T_{2c} data was modified to yield the T_{2c} (compromised) data in Table 3.

Plots between ductile components and T_{2c} (compromised) values are presented in Figures 12 and 13. The two figures present different correlations, logarithmic on Figure 12 and linear in Figure 13. The correlations are

$$T_{2c} = 22.096 \ln(V_{dc}) + 1.2341 \qquad (2)$$

and

$$T_{2c} = 1.6672 \; (V_{dc}) + 33.697 \qquad (3)$$

where V_{dc} is percentage of ductile component.

With the establishment of equations (2) and (3), any T_{2c} values can be estimated whenever ductile components data becomes abailable. Following the same manner, comparison between NMR S_{wirr} and core S_{wirr} can be performed (Figures 14 and 15). Comparisons in the two figures appear to be a tendency of more optimistic estimated Swirr, indicated by lower NMR S_{wirr} compared to core S_{wirr} values.

Comparisons presented in Figures 14 and 15 have also shown that the establishment of general functions of equations (2) and (3) does not seem to help improving the agreement between NMR S_{wirr} and core S_{wirr}. This is true when they are compared to comparison presented in Figure 11, on which the T_{2c} value used is simply the average of T_{2c} values from BVI Error method.

In addition to Figures 14 and 15, Figure 16 presents comparison between NMR S_{wirr} and core S_{wirr} with the use of averaged T_{2c} (compromised) value of 53.17 ms. From the figure it can be seen that slight improvement has been made when compared to Figures 14 and 15, and this improvement appears to have made plot in Figure 16 to resemble the plot in Figure 11. Again, up to this point it can be said that, despite the theoretical soundness of the empirical correlations, T_{2c} averaging appears to be adequate for yielding representative T_{2c}.

For the third option, five plots will be made, which h are comparison between core S_{wirr} and NMR S_{wirr} estimated using true T_{2c} values from BVI Error method: 32, 62, 70, 75, and 90 ms (Table 3). The comparisons are presented in Figures 17 through 21.

From Figures 17 through 21 it is obvious that good agreement between core S_{wirr} and NMR S_{wirr} are shown by NMR S_{wirr} values that are estimated using T_{2c} of 62, 70, and 75 ms. This suggests that the most representative T_{2c} for the six Tirrawarra sandstone samples used in the study should be around 70 ms, and if an averaged value is to be taken from the three values then it is 68.5 ms (i.e. this also counts as the fourth option, T_{2c} value picking). Notice the closeness of this value to the overall average T_{2c} of 66.5 ms (Figure 11).

VI. CONCLUSIONS

From the study that has been conducted, several main conclusions can be derived. The conventional use of a standard single NMR relaxation cut off time (T_{2c}) values and varied T_{2c} values directly measured from spectrometer is not appropriate for NMR application on ductile shaly sandstones with high irreducible water saturation. It shows that a fixed or single predetermined T_{2c} would underestimate the “true” BVI and S_{wirr} values. BVI Error method appears to be the best method for providing varied T_{2c} values when compared to T_{2c} from SBVI and directly from spectrometer.

When the question comes into what T_{2c} value(s) are to be used for applied NMR log interpretation, comparisons shown using the four options have revealed that even for the case of shaly Tirrawarra sandstones, simple averaging seems to be adequate to yield a reliable single T_{2c} value. On the other hand, although establishment of empirical correlation may be theoretically more sound, results show that estimated NMR S_{wirr} values produced are less accurate compared to simple averaging. Careful T_{2c} value picking also indicates a result that is close to result from simple averaging.

The overall conclusion of this study is certainly true for the ductile Tirrawarra sandstones used. Results may differ for other cases even though arguably the conclusion may also apply to other sandstones, especially for ones with level of complexities less than the highly heterogeneous Tirrawarra sandstones.

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